

## Solid State Digital “Cluster Thrusters” For Small Satellites, Using High Performance Electrically Controlled Extinguishable Solid Propellants\*

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**Abstract:** Electrically controlled extinguishable solid propellants (ECSP) are capable of multiple ignitions, extinguishments and throttle control by the application of electrical power. Both core and end burning *no moving parts* ECSP grains/motors to three inches in diameter have now been tested. Ongoing research has led to a newer family of even higher performance ECSP providing up to 10% higher Isp, manufacturing ease, and significantly higher electrical conduction. The high conductivity was not found to be desirable for larger motors; however it is ideal for downward scaling to micro and pico-propulsion applications with a web thickness of less than 0.125 inch. As a solid solution propellant, this ECSP is molecularly uniform, having no granular structure. Because of this homogeneity and workable viscosity it can be directly cast into thin layers or vacuum cast into complex geometries. Both coaxial and grain stacks have been demonstrated. Combining individual propellant coaxial grains and/or grain stacks together form three-dimensional arrays of *modular cluster thrusters*. Adoption of *fabless* manufacturing methods and standards from the electronics industry will provide custom, highly reproducible micro-propulsion arrays and clusters at low costs. These stack and cluster thruster designs provide a small footprint saving spacecraft surface area for solar panels and/or experiments. The simplicity of these thrusters will enable their broad use on micro-pico satellites for primary propulsion, ACS and formation flying applications. Larger spacecraft may find uses for ECSP thrusters on extended booms, on-orbit refueling, pneumatic actuators, and gas generators.

*\*Patents Pending, Digital Solid State Propulsion Company and ET Materials LLC*

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### Introduction

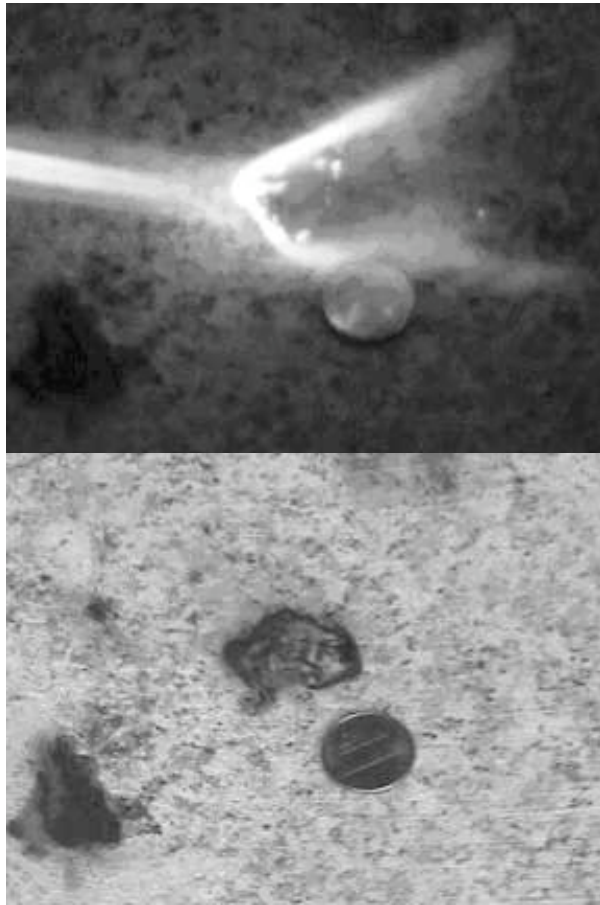
Solid propellant rocket motors (w/ no moving parts) have previously included many problems with controllability/restarting and explosion hazard probably foremost<sup>1</sup>. This began to change in 1999; under Air Force SBIR funding we developed the first electrically controlled extinguishable solid propellant (ECSP), known as “ASPEN”. Multiple ignitions, extinguishments and throttle control of ASPEN propellant have been demonstrated by the application of electrical power. These propellants are insensitive to ignition by flame and are both non-self sustaining/initiating without the application of proper electrical power (figure 1). Continuous exposure to high temperature flame may eventually over heat the ECSP where smoldering may occur, however this low energy combustion is completely avoidable with proper thermal control via duty cycle.

Both core and end burning *no moving parts* ECSP grains/motors to three inches in diameter have now been tested using a composite ECSPs that are most

suitable for motor scale up. We now have two completely different propellants that may be considered electrically controllable. Each propellant alone or in combination is likely suited to one application better than another. ECSPs however, have not been found to be suitable for pulsed plasma thrusters (PPT) fuel replacement for Teflon. PPTs use an electrical plasma arc to vaporize the propellant surface<sup>2</sup> and the ECSPs are generally electrically too conductive to allow arc formation before “shorting” through the propellant.

### Higher Performance ECSP

Ongoing research has also led to a new family of even higher performance ECSP in the form of solid solution propellants. These propellants provided up to 10% higher performance than composite ECSP, but are significantly more electrically conductive. The high conductivity was not found to be desirable for larger motor scale up, however it is ideal for downward scaling to micro and pico propulsion applications. As a solid solution propellant, it is molecularly uniform,



**Figure 1. Higher Performance ECESP illustrating insensitivity to ignition by torch flame (top). The ECESP chars but does not burn (bottom). A penny is included for scale in both photographs.**

having no granular structure. The high performance ECESP is also a “manufacturing friendly”, low hazard material that can be room temperature mixed and cast with a reasonable pot life. Because of its homogeneity and viscosity it can be cast into thin layers or vacuum cast into complex geometries.

Like other ECESPs, combustion is sustained only when proper electrical power is supplied; coaxial and “stacked” layers of the propellant can be ignited separately or in combination without causing unwanted ignition of a neighboring propellant. A grain stack design provides new versatility over previous “thrusters on a chip” demonstrations that utilize conventional solid propellants. The design/construction is similar, to other chip thrusters with the notable difference that each thruster could be fired numerous times. Combining these individual propellant coaxial grains and/or stacks together into three-dimensional arrays

yield *modular cluster thrusters*. The stack cluster thruster design provides a small footprint saving spacecraft surface area for solar panels and/or experiments.

High performance ECESP grain stacks may be configured either for electrical conduction between planar or in coaxial electrode configurations (figure 2). Adoption of “fabless” manufacturing methods and standards from the semiconductor industry should provide custom, highly reproducible downward scaling of micro to pico propulsion arrays/clusters at low costs.



**Figure 2. Coaxial solid-state microthrusters 1/8”-1/4” in diameter ready for testing.**

### Testing and Demonstration

Coaxial, end burning ECESP micro-thrusters have been successfully demonstrated with a web thickness from 0.060 to 0.125-inch and up to 1-inch long. The ECESP initiates at the upper burning surface, extinguishes on-demand and restarts (figures 3 and 4). Using a hand-operated switch/controller up to 12 or more pulses have been produced from a 0.125 by 0.50-inch grain under ambient conditions. Testing found both stainless steel and aluminum to be suitable for use with the higher performance ECESP while phenolic and Teflon are suitable as insulation. Our testing also demonstrated the importance not over heating grains, as this leads to ECESP smoldering. Without active direct cooling of the ECESP grains, propulsion duty cycles of <20% may be expected.

These coaxial thrusters may also be bunched or clustered into arrays that may be fired randomly or in concert for even greater thrust. The small size and conformity to many commercial electrical components, should allow these micro-thrusters to be mounted and wired directly to circuit boards along with controllers and power supply.



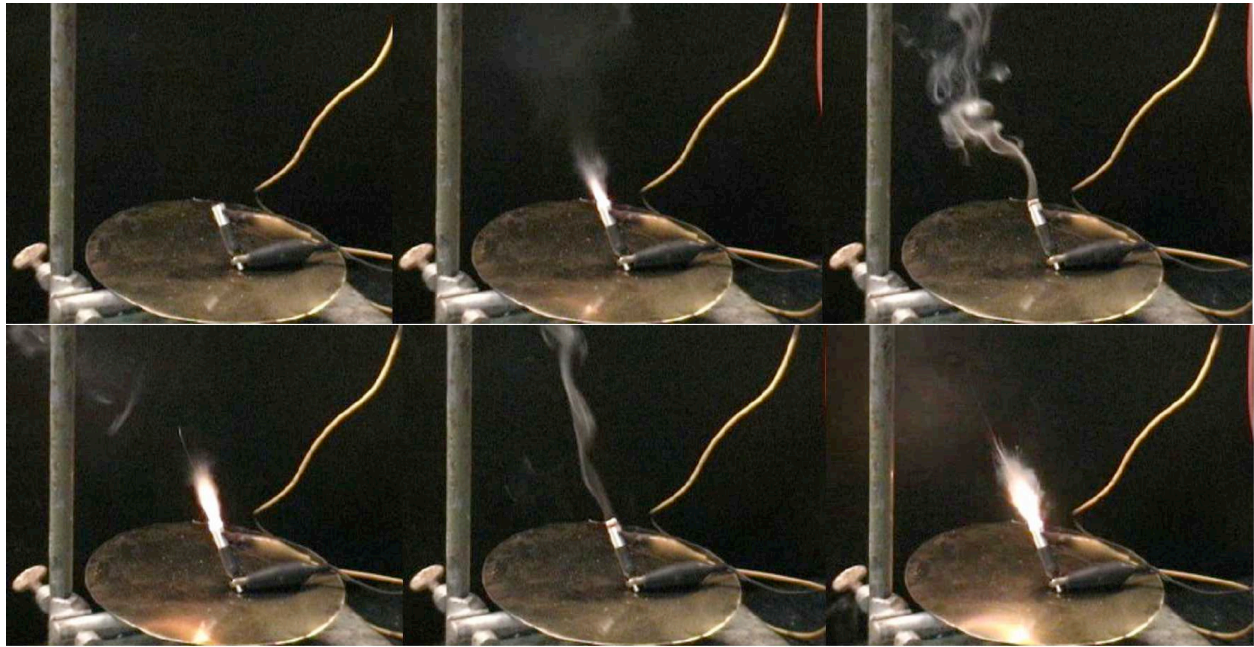


Figure 3. A 0.25 inch diameter coaxial micro-thruster illustrating repeated restarts.

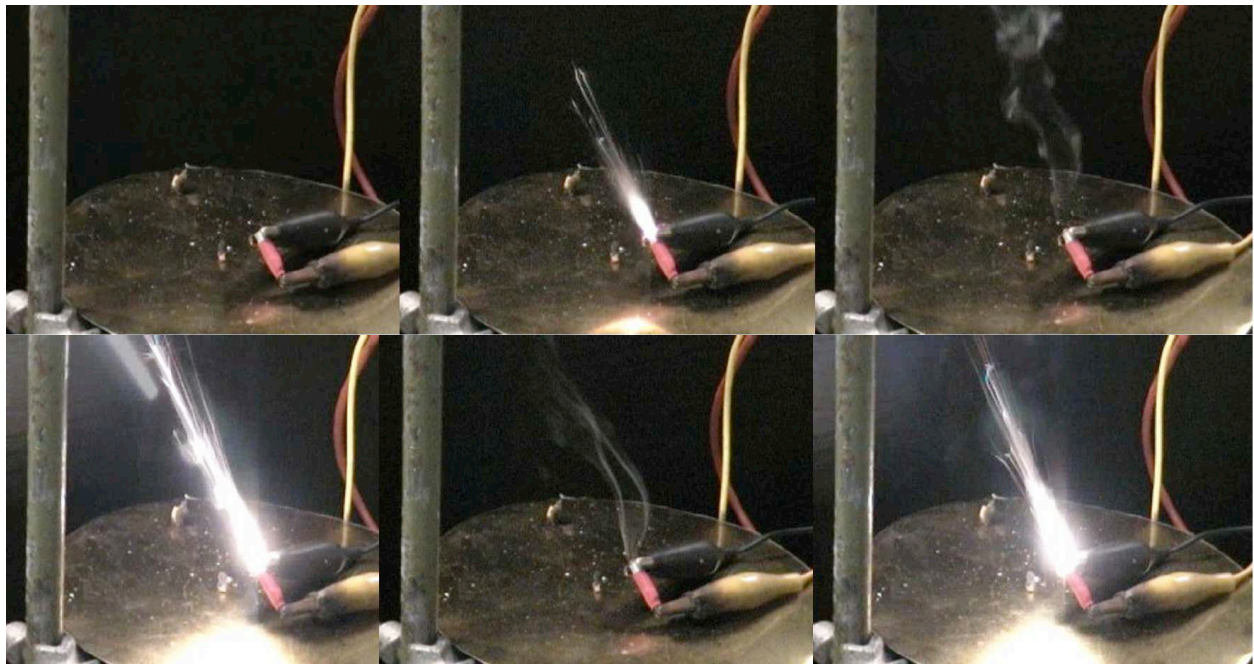


Figure 4. A 0.125-inch diameter coaxial thruster demonstrating both restart and throttle control.

#### ECESP Gas Generation and Warm Gas Thrusters

The ECESPs appear attractive as solid-state on-demand gas generators. These solid-state gas generators should be “nearly” drop in replacements for some existing cold and warm gas propulsion units. Our electrically

controlled solid propellant combined with commercially available micro-solenoid valves appear to provide a the basis for a versatile, low cost *unified warm gas thruster module*, with on-demand tank re-pressurizations. Commercially available micro solenoids are currently specifying minimum impulse

bits down to 44mN seconds. Table 1 and 2, provide some initial estimates of the relative mass of various components to a 400N-sec total impulse, unified 6-axis ACS thruster weighing about 500 grams.

The propellant mass fraction in this example is around 40% with an overall combustion chamber aspect ratio of six. Higher case/combustion chamber aspect ratios would yield somewhat higher propellant mass fractions. Table 2 compares the notional thruster with the highly maneuverable SPHERES nanosatellite cold gas

thruster<sup>3</sup>. With both thruster systems weighting about half a kilogram, the ECESP Notional thruster would contain more that double the gas volume available for propulsion. An average ECESP is used as the baseline propellant for this modeling. However, ECESPs have been principally formulated for high Isp, not as gas generator. Future reformulation of the ECESPs for gas generation is likely also possible. Both the ECESP and combustions products are relatively benign and safe with no special handling requirements.

**Table 1. ECESP Notional Warm Gas Thruster Mass Summary for ~400 N/sec total impulse @ < 0.5 kg (assumes trickle charging the motor capacitor from spacecraft solar power system). Overall dimensions of this notional module are 38mm in diameter by 250mm long.**

COMPONENT	WEIGHT
Micro-solenoids (6 @ 6 gm)	36 gram
Main engine solenoid* (1)	20
Thruster Case (combustion chamber)	135
Propellant	185
Filter/water conversion, insulation, nozzles	40
Plumbing/mounting	20
Supplemental electrical	40
Margin	24
Total	500 grams

**Table 2. Comparison of the joint MIT and Payload Systems Inc. SPHERES nanosatellite (3.56 Kg total) thruster system with the *notional* ECESP warm gas thruster system here.**

SYSTEM	THRUSTER MASS	PROPELLANT MASS	TOTAL GAS @ STP
Notional ECESP Warm Gas	500 grams	185 grams	199 liters*
SPHERES CO <sub>2</sub>	517 grams	170 grams	87 liters

\* Assumes conversion of combustion water to H<sub>2</sub> using lithium hydride etc.

### Future ECESP Applications

The ECESP is very attractive for refuelable satellite applications, such as DARPA's Orbital Express Program<sup>4</sup>. The major advantage of using ECESP solid-state propellant for satellite refueling is simplicity and non-hazardous storability. Currently, Orbital Express envisions using three different fluid couplers to transfer hydrazine, MMH and NTO<sup>5</sup>. Leakage of any of the liquid couplers during repeated docking maneuvers could result in damage to sensors systems or at worse catastrophic loss of one or both spacecraft. Safely transferring energetic liquids in space is proving to be both difficult and expense. Alternatively, servicing

spacecraft by transferring solid propulsion modules utilizing ECESP thrusters would eliminate both complexity and potentially dangerous liquid spills in space. Storable, "blocks" of cluster thrusters can provide for simple on-orbit "plug-and-fire" robotic change outs with high redundancy not available with liquid systems. *The mechanics for changing out solid-state thrusters on satellites should be no more complex than changing batteries in a flashlight.*

Other advantages for using the ECESP include: low chance of accidental ignition, nontoxic, storable, low part count, no moving parts and no potential gas or liquid leaks to damage the high valuable assets. These

same characteristics also make these propellants very desirable for use in man rated flights. The variable thrust capability demonstrated in this study also has a broad application to ACS for space or missile systems. Our digital solid-state propulsion technology could also be used to produce a DACS with no moving parts, ideal for storable tactical missile application.

Other emerging application for this propulsion technology is airships/aircraft (re: NASA, Mars Flyer<sup>6</sup> operating in near space (~100,000ft.). Propeller propulsion, while possible at these altitudes is slow to react and inefficient, while more efficient space propulsion (ion engines), cannot operate with the high atmospheric backpressures at <250,000 ft.<sup>1</sup>. ECESP could provide these future high stratospheric vehicles with safe ground handling (unlike hydrazine) and controlled, on-demand thrust for controlled flight or emergency propulsion maneuvers.

The simplicity of these thrusters should enable their broad use on micro satellites for primary propulsion and formation flying and their rapid re-tasking<sup>7, 8</sup>. Larger spacecraft may find uses for such tiny thrusters on extended booms, on orbital refueling by robotic change out, pneumatic actuators and in precise positioning requirements for deep space spectrometry missions.

### Technology Commercialization

We are currently applying our controllable solid propellant technology to developing a controllable dual-stage tactical rocket motor for the Army (AMCOM) under an SBIR Phase II program and a MEMS thruster for NASA under a Phase I contract among other projects.

The ECESP grain and electrode design demonstrated herein is very compatible with standard electronics manufacturing. This manufacturing compatibility provides another potential very important non-space application, which is the use of these ECESP as on-demand gas generator for pneumatic actuators. Using our propellants for on demand gas generation may be highly effective in enabling whole new class autonomous pneumatic robotic devices, with simple replaceable gas generators. Smart automotive airbags are also a potential area of application for this technology, once DOD applications are proven and releasable to commercial industry.

### Acknowledgements

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